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# Is there a hole in the NuMI target?

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MINOS has observed a steady reduction in the neutrino rates at the ND since the beginning of Run II. The reduction is rate is most prominent in the low energy $< 6$ GeV region and no perceptible reduction in the region with $> 6$ GeV. The drop observed is about 2.5% in Run II with an integrated POT of 2.13 E20 and about 5.0% in Run IIIa (using the same target) with an integrated POT of $\leq$ 1E20. Target damage due to irradiation has been proposed as one of the possible explainations for observed reduction in neutrino flux. In this note we present a simple emperical method for assesing the effect of a "hole" in the target through reweighing the hadron production spectrum in GNUMI. We have applied this method to various size "holes" at different locations along the target and we find we can reproduce the effects seen in the data qualitatively : a significant reduction in the neutrino energy spectrum in the region of 2-5GeV with a much smaller increase in the rate $>$ 6GeV.

# 1 Introduction

MINOS has observed a steady reduction in the neutrino rates at the ND since the beginning of Run II. The reduction is rate is most prominent in the low energy $< 6$ GeV region and no perceptible reduction in the region with $> 6$ GeV. The drop observed is about 2.5% in Run II with an integrated POT of 2.13 E20 and about 5.0% in Run IIIa (using the same target) with an integrated POT of $\leq$ 1E20. The beam profile is approximately Gaussian with a width of 1.0-1.2mm. This corresponds to around 6.5E21 POT/cm$^2$ in the 1 $\sigma$ core of the beam. The region where the reduction is most pronouned is in the region 2-5 GeV (DocDB ???) wheras no significant effect is seen in neutrino energies $> 6$ GeV.

From a long disussion with Jim Hylen, there are many effects that could degrade the target:

1. Irradiation: the effect of irridation was modeled using MARS and scaling from low energy neutron measurements from graphite at reactors. The low energy neutron data indicated that graphite could actually get more dense in the beginning. The largest energy deposition was estimated using a MARS simulation to be approximately at the 6th segment from the upstream end of the target (the NuMI target is made of 47 graphite segments 6.4 mm wide, 1.8 cm in height and 2cm in length). Irradiation of a graphite target using high energy protons has been carried out recently at BNL. The actual details of the experiment are not yet known and may not be relevant for NuMI, but preliminary results indicate that there might be a "swelling" of the target at the point of largest energy deposition. The BNL results indicate that irradiation effects would start to manifest themselves at an exposure of around $10^{22}$ POT/cm$^2$ and the rate of degradation of the target accelerates with time.

2. Evaporation of the graphite: The NuMI target is currently bathed in helium, one possible effect that could be taking place is evaporation of the graphite when its heated up. Jim mentioned that graphite is destroyed at a temperature of 420 C but our target is cooled so its unlikely we reach these temperatures.

3. Oxidation: The He used in the NuMI target is high purity, but it will still contain some oxygen especially if we have a small leak in the target housing. The ionization of oxygen due to irradiation by the beam would make it more reactive and the target could be chemically altered due to oxidation. This, like the evaporation would cause a change or depletion in the envelop of the target segments as opposed to irradiation damage which would be concentrated near the core of the energy deposititition.

4. Helium pressure in the target: Another effect would be the separation of the graphite layers due to pressure exerted by He permeating the target which would expand when heated.

## 2 Simulated target geometry

A photograph of the NuMI target is shown in Figure 1. The photo shows the location of the graphite segments, the cooling lines, cooling rings and upstream fin.

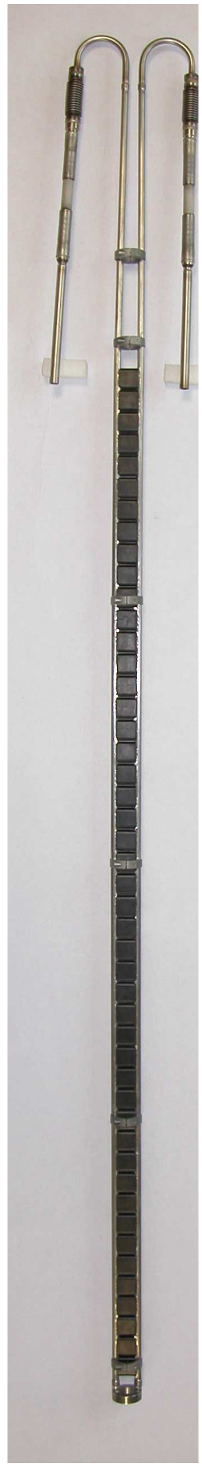


Figure 1: Photograph of the NuMI target

The implementation of the target geometry in FLUKA05 used in GNUMI version 18 and 19 (by Francisco Yumiceva and Bob Zwaska) is summarized in Table 1. The rendering of the FLUKA05

Table 1: Summary of target elements in the FLUKA05 simulation in the LE position.

| Element | shape | Location in x | Location in y | Location in z |
|---|---|---|---|---|
| Al casing | cyl | $0, r = 1.46 - 1.50$ | $0, r = 1.46 - 1.50$ | -54 +116.05 |
| Upstream Be window | cyl | $0, r = 1.46$ | $0, r = 1.46$ | -54 +0.0254 |
| Horizontal fin | rounded rect | -1.0 to 1.0 | -0.094 to 0.546 | -51.42 to -50.06 |
| Cooling line 1 | cyl | $0, r = 0.3$ | $1.05, r = 0.3$ | -44 +104.6 |
| Cooling line 2 | cyl | $0, r = 0.3$ | $-1.05, r = 0.3$ | -44 +104.6 |
| 47 target fins | rounded rect | -0.32 to 0.32 | -1.0 to 1.0 | -34.68 to 60.06 |
| Water ring | cyl | $0, r = 0.73 - 1.41$ | $0, r = 0.73 - 1.41$ | 60.5+0.56 |
| Downstream Be window | cyl | $0, r = 1.415$ | $0, r = 1.415$ | 61.85 +0.05 |

target geometry is shown in Figures 2, 3, 4.

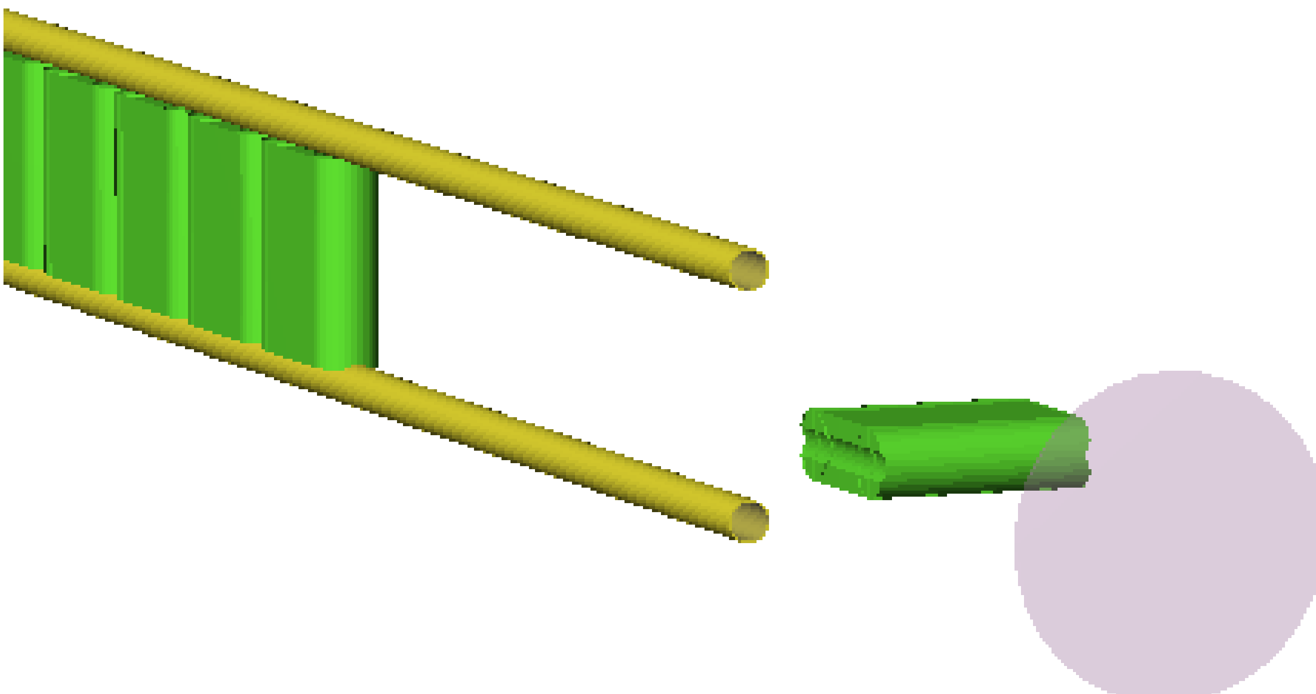


Figure 2: Upstream end of the NuMI target with the horizontal fin and the upstream Be window.

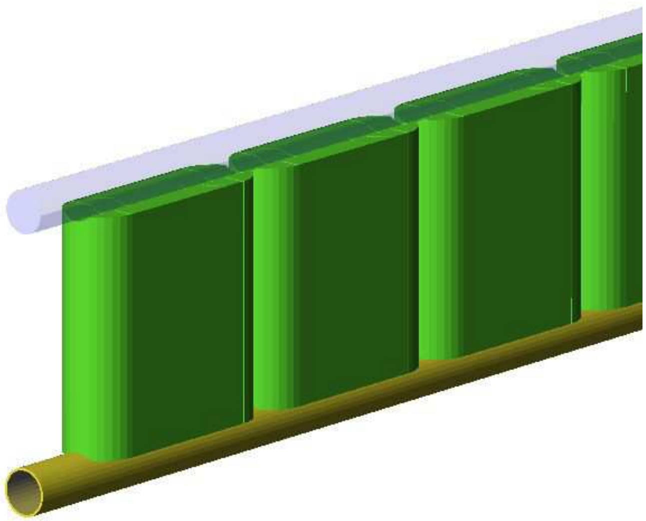


Figure 3: Graphite fin with cooling rings

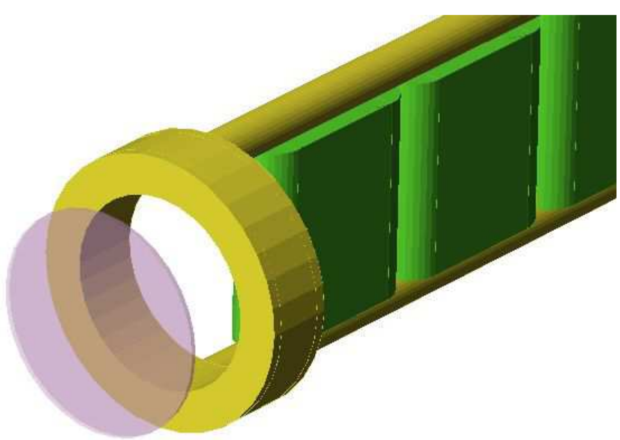


Figure 4: Downstream end of the NuMI target with the water ring and the downstream Be window.

# 3 Hadron production in the NuMI target

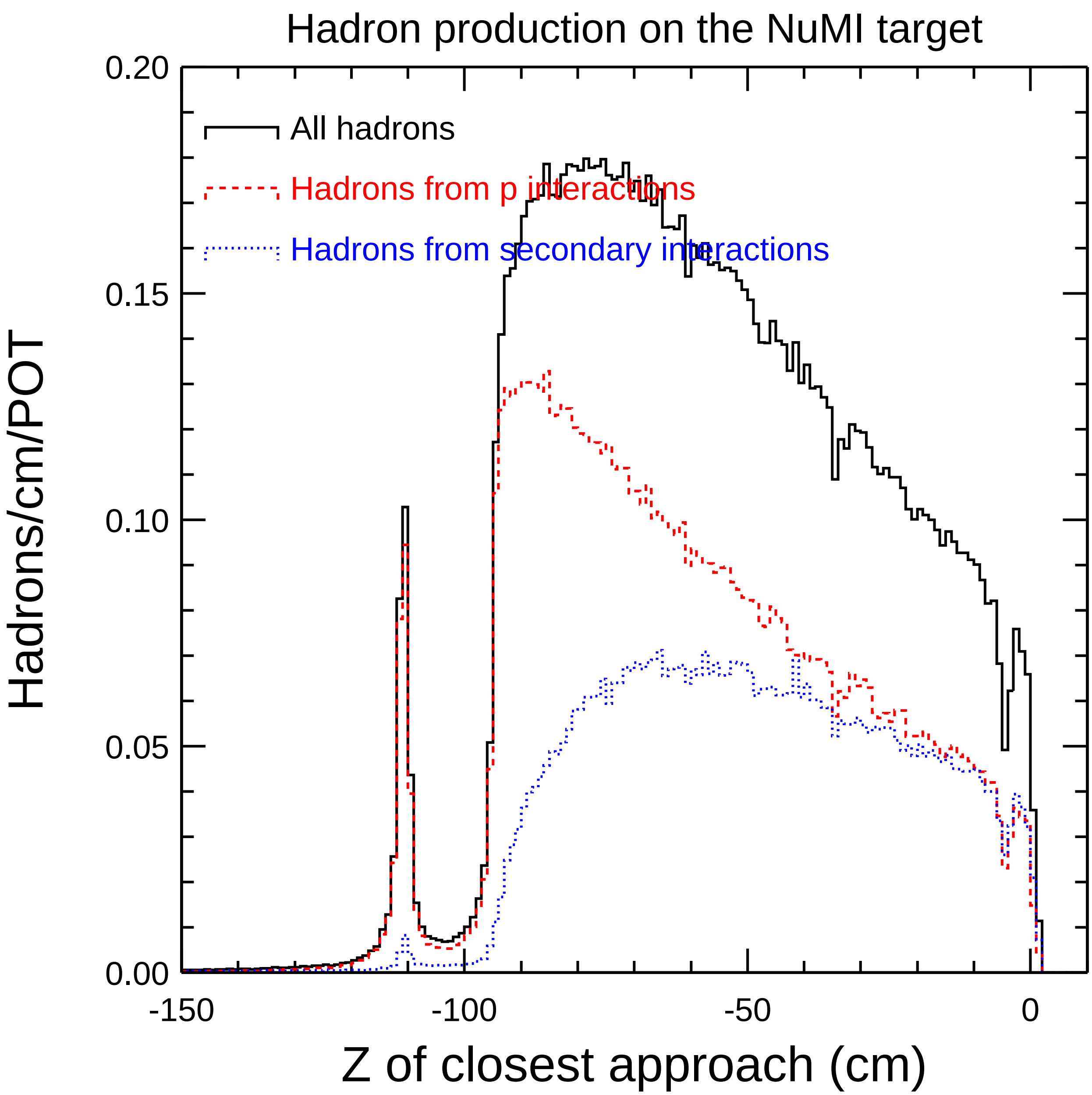



Figure 5: The number of hadrons produced per proton in the FLUKA05 simulation of the NuMI target as a function of z location at the point of closest approach to the target axis. Z=0 is the downstream edge of the last graphite segment. The distribution of hadrons from primary interactions are shown in red and from secondary interactions in blue. The horizontal fin is located between z=-111.48 and z=-110.12cm.

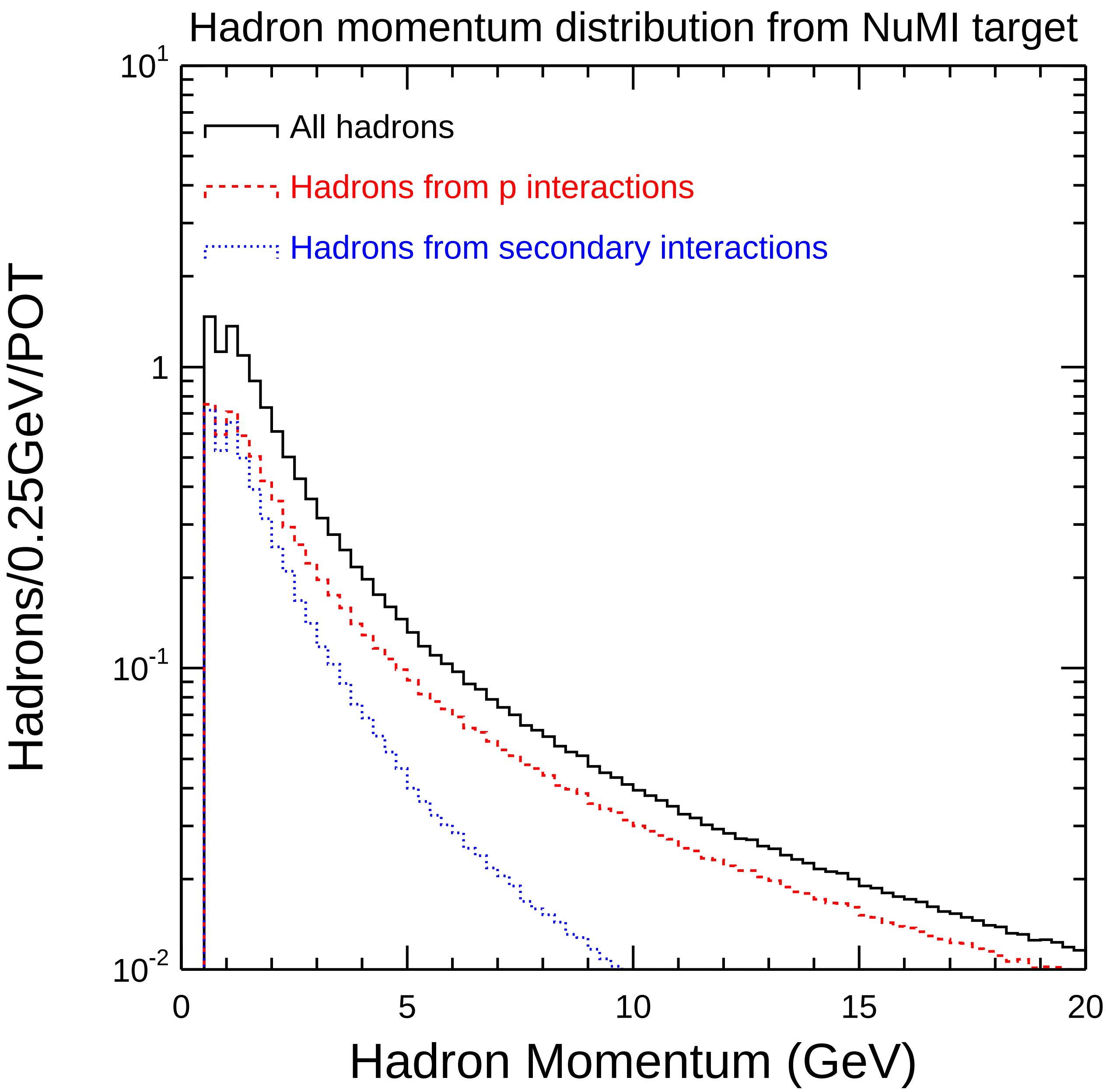



Figure 6: The total momentum distribution of hadrons produced by the FLUKA05 simulations primary interactions are shown in red and from secondary interactions in blue. Before focusing.

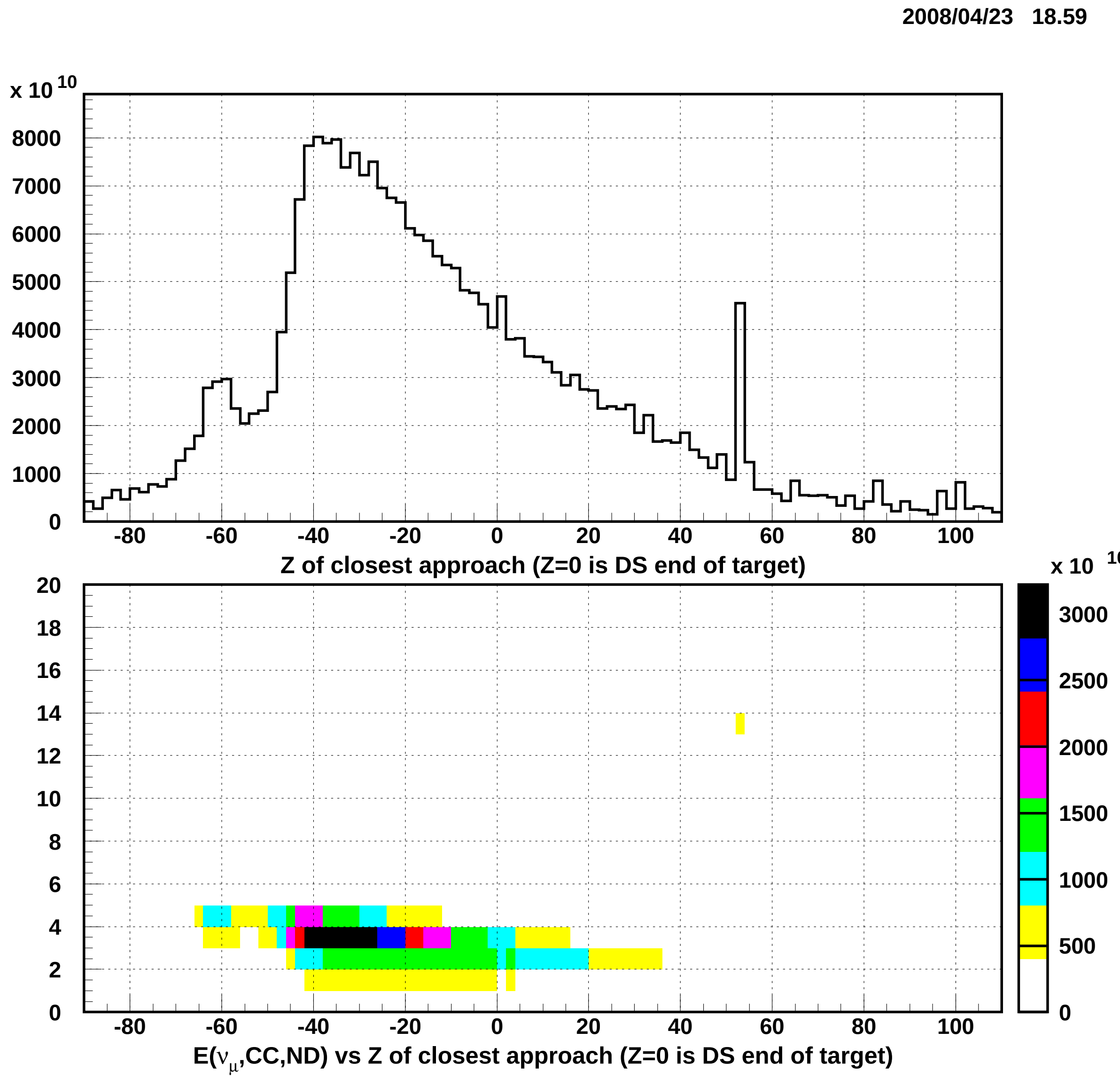



Figure 7: Top: the distribution of hadrons which produce neutrinos in the MINOS ND as a function of z location at the point of closest approach to the target axis in the LE-10 GNUMI simulation. The upstream end of the last target segment is at z=50.06cm, the upstream face of Horn 1 is at z=0cm and the horizontal fin is centered at z=-60.74.. Bottom: The energy of neutrinos from decays of hadrons produced in the target (y-axis) vs the production location of the hadron at the distance of closest approach to the target axis.

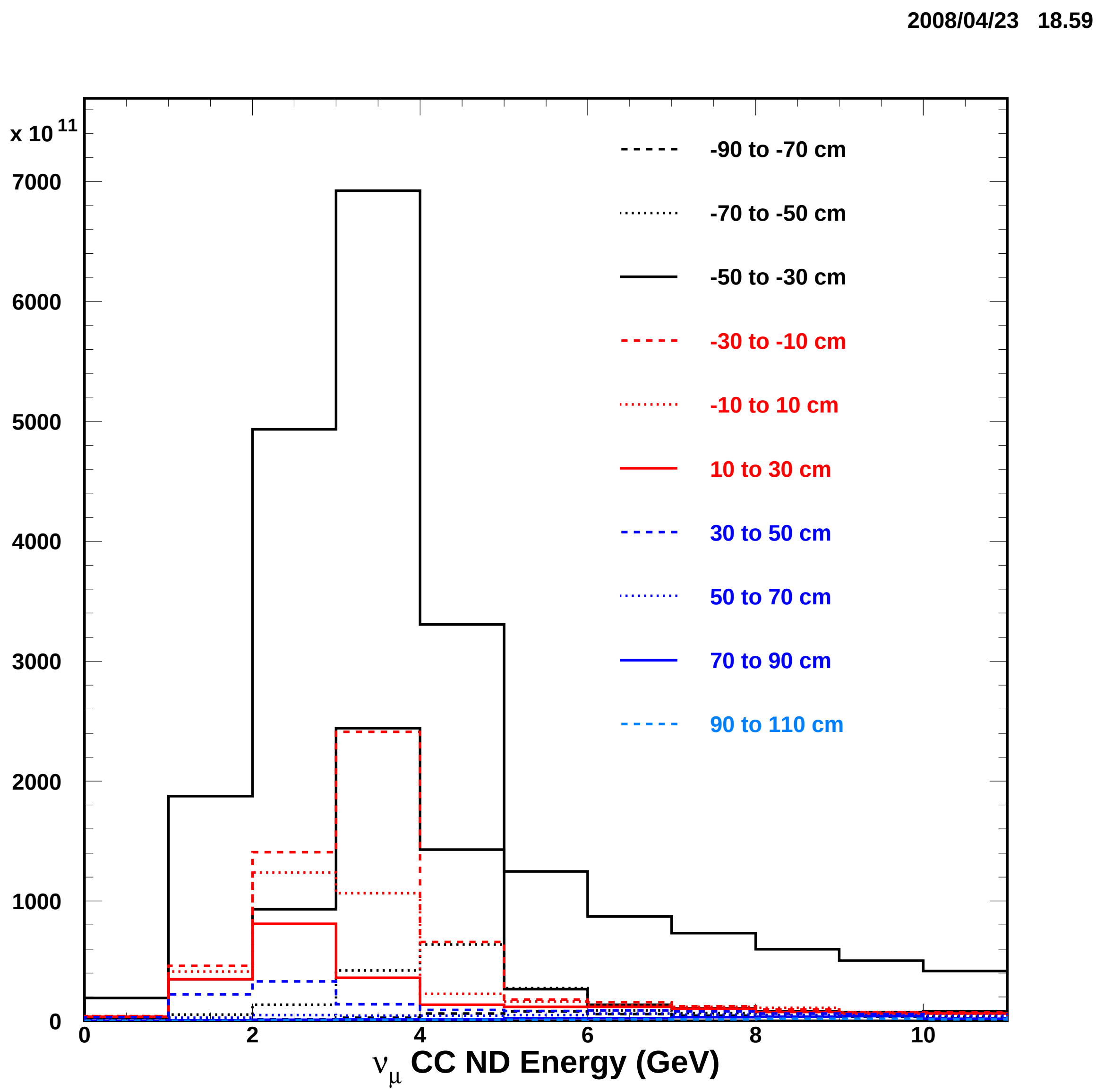



Figure 8: The spectrum of neutrinos originating from the decays of hadrons produced at different locations along the target axis. The graphite segments are located between -44.68cm and 50.06cm (LE-10). The horizontal fin is centered at z=-60.74.

# 4 A "hole" in the target

We "simulate" the prescence of a "hole" in the target by removing neutrino events that originate from hadrons coming from a section of target between $z_{hole}$ and $z_{hole} + \Delta z_{hole}$ where $z$ is the location of closest approach of the hadron trajectory in the z co-ordinate to the target axis. A missing portion of the target would mean that more hadrons interact upstream of the hole, so in addition to removing neutrino events originating from decays of hadrons produced in the hole, we increase the weight of neutrino events originating from decays of hadrons upstream:

$$\begin{aligned} P'(z) &= P(z) \text{ if } z < z_{hole} \\ P'(z) &= 0 \text{ if } z > z_{hole} \text{ and } z < z_{hole} + \Delta z_{hole} \\ P'(z) &= P(z - \Delta z_{hole}) \text{ if } z > z_{hole} + \Delta z_{hole} \end{aligned}$$

$P(z)$ is original probability that a near detector neutrino originated from a decay of a hadron at $z$ and $P'(z)$ is the new probability with a simulated hole in the target. In principal, neutrinos originating from decays of hadrons produced in primary and secondary interactions in the target should be reweighed separately, but for this preliminary analysis we reweigh neutrinos from all hadrons in the same manner since the required information is not available in the GNUMI ntuples. An example of the reweighing schemes is shown in Figure 9

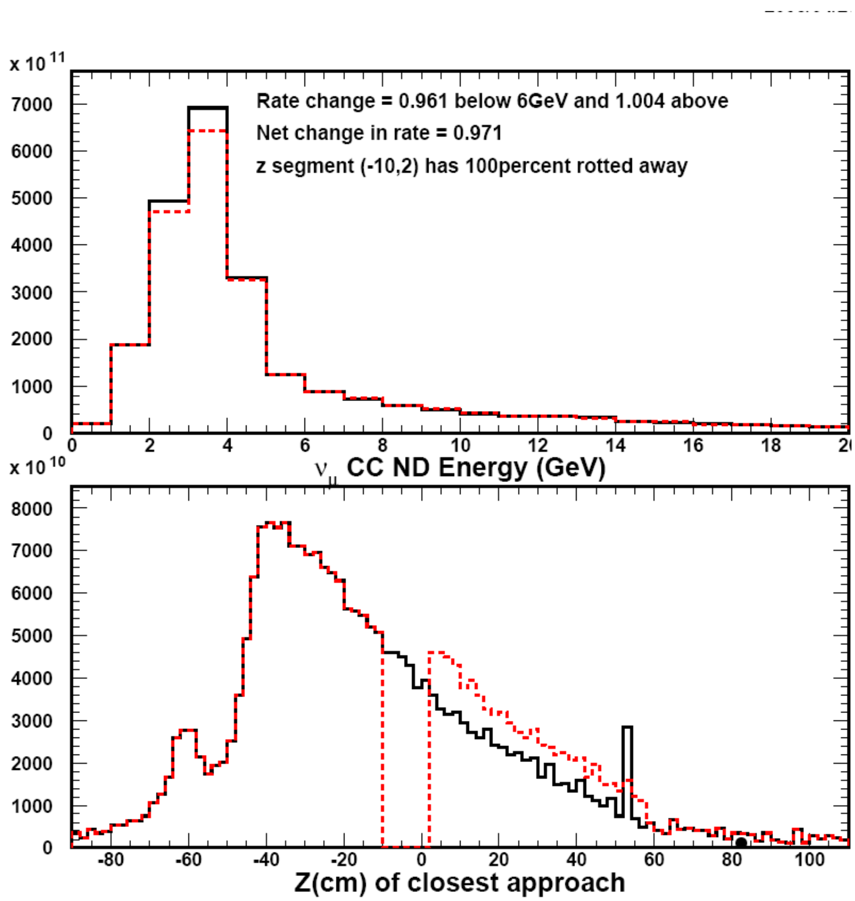
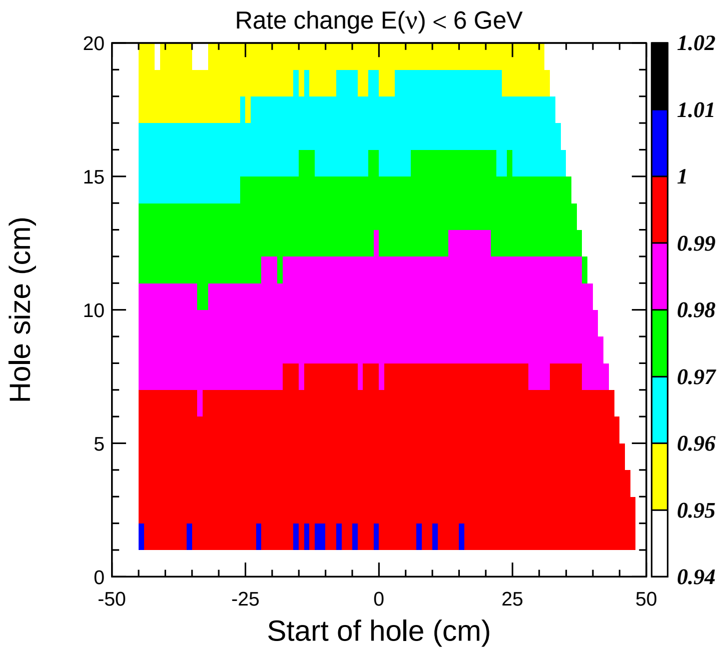



Figure 9: Simulation of a hole in the target. Top: The original neutrino CC spectrum in the MINOS ND (black) and the neutrino CC spectrum produced by simulating a hole in the target (red). Bottom: The number of hadrons producing neutrinos in the ND as a function of z location of closest approach to the target axis. The graphite segments are located between -44.68cm and 50.06cm (LE-10). The horizontal fin is centered at z=-60.74.Top: The nominal neutrino CC spectrum (black) and the effect of a hole in the target (red).

# 5 Results

We varied the beginning location of the hole all along the target in 1cm increments and varied the size of the hole from 1-20 cm. The ratio of the observed CC rate to nominal in the region $< 6$ GeV and $> 6$ GeV is shown as a function of the hole location and size in Figure 10. We find that for holes of greater than 8cm with locations starting from the upstream face of the target and up to 20cm into the target, the rate $< 6$ GeV is reduced by a few % but the CC rate $> 6$ GeV stays the same or increases slightly. This is consistent with the effect we observe in the MINOS ND. If the damage starts very close to the upstream end of the target, its possible that as the damaged area increases we could see a small increase in the high energy rate.



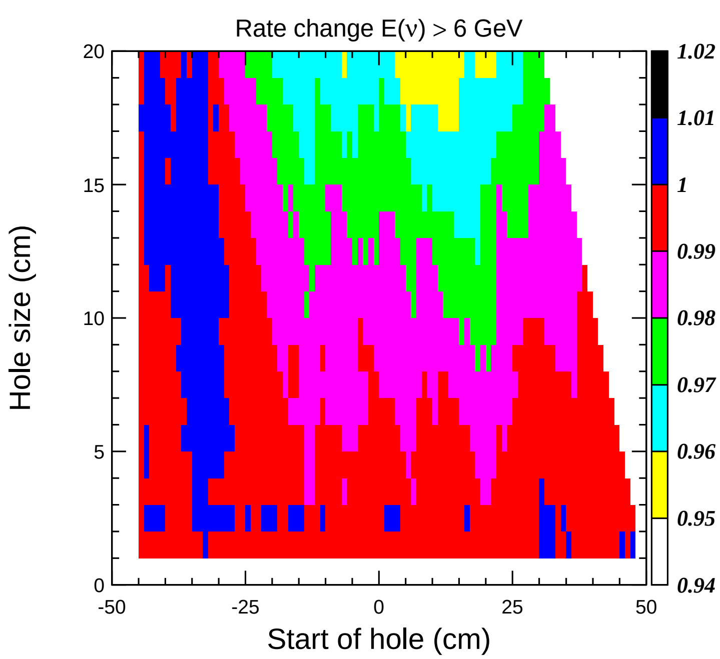




Figure 10: Effect of hole on the neutrino rate $< 6$ GeV (top) and $> 6$ GeV (bottom)

# 6 Conclusion

In this note we presented a simple emperical method for assesing the effect of a “hole” in the target through reweighing the hadron production spectrum in GNUMI. We have applied this method to various size “holes” at different locations along the target and we find we can reproduce the effects seen in the data qualitatively : a significant reduction in the neutrino energy spectrum in the region of 2-5GeV with a much smaller increase in the rate $>$ 6GeV.